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Cold Regions Research &
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Ice Engineering

U.S. Army Engineer Research and Development Center, Hanover, New Hampshire

Method to Estimate River Ice Thickness Based on Meteorological Data

Some knowledge of ice thickness is required for the design of structures—such as bridges, dams, weirs, locks, piers, intakes, channel stabilization measures, and coastal shoreline protection—in ice-affected rivers. One recent case illustrating the need for considering ice in the design of riverine structures is the failure of the McKeesport (Pennsylvania) Marina on the Youghiogheny River in January 2001 (Fig. 1 [Silver and Fuoco 2001] and 2). The marina was constructed in 1997 at a cost of more than \$2 million. According to the ERDC-CRREL Ice Jam Database sources (National Weather Service 2001a, b; Veltri 2001), ice jam breakup, jamming, and failure resulted in the complete destruction of the marina by chunks of ice measuring up to one foot thick. Contemporary reports estimated that the damage began around 6:30 p.m. on 31 January, and by 8:37 p.m., the marina was torn away. Reconstruction costs for the marina have been estimated at more than \$1 million.

Ice covers and ice jams can cause rapid increases in stage that can cause flooding and damage (Fig. 3). Numerical models of rivers to develop stage-frequency information required for modeling ice jams for flood damage reduction measures, flood insurance studies, and changes to the ice regime that occur from development in the floodplain or dam removal also require that ice thickness be estimated. Analyses of ice-induced scour and erosion in ice-affected rivers must include knowledge of ice thickness.

Unlike discharge or stage measurements, observations of ice thickness can be challenging to locate. The USGS does record ice thickness as part of its winter discharge measurements, but these records are often archived in paper form and can be difficult to access. Some local flood warning systems measure ice thickness. A good example is the Nebraska Ice Warning System (<http://dnrdata.dnr.state.ne.us/Icejam/index.asp>), which contains seasonal ice thickness measurements.



Figure 1. Twisted docks at McKees Point Marina on the Youghiogheny River, Pennsylvania. Photo by Darrell Sapp, Post-Gazette.

Given the lack of existing data, ice thickness must often be estimated. Because ice covers result from complex physical processes, there is not yet a method to account for all factors affecting thickness. This technical note presents a method to estimate ice thickness that results from heat transfer processes based on meteorological data.

Figure 2. Debris from the McKeesport Marina trapped above Emsworth Locks and Dam on the Ohio River about six miles downstream from Pittsburgh. Photo by Andy Tuthill, ERDC-CRREL.

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Figure 3. Hydraulic modeling of ice jams requires some estimate of ice thickness.

Ice Formation

River ice covers form initially in processes ranging from the purely static to the purely dynamic. Static ice cover formation is a largely thermal process in that the initiation and growth of ice covers result from heat transfer between the water and the atmosphere. Statically initiated ice covers in rivers are found in quiescent areas and along the edges (border ice). The U.S. Army Corps of Engineers Ice Engineering Manual (USACE 2002, <http://www.usace.army.mil/inet/usace-docs/eng-manuals/em1110-2-1612/toc.htm>) contains a detailed description of the heat transfer processes that result in initial ice formation.

Dynamic ice cover formation results from the mechanical processes associated with ice floe interactions. These may range from relatively low-energy processes such as the juxtaposition of ice floes into a single layer of ice that then freezes in place, or higher-energy processes such as the accumulation of floes into an ice jam by shoving and internal collapse. Once formed, ice covers can also thicken via thermal processes, by flooding and refreezing of the surface, or by deposition of ice beneath the surface.

Ice formation and thickening are also described and reviewed in Ashton (1986), Beltaos (1995), and White (1999, http://www.crrel.usace.army.mil/techpub/CRREL_Reports/reports/CR99_11.pdf), which provides a review of the properties of ice used in hydraulic modeling of ice. It is not yet possible to predict ice thickness resulting from dynamic processes, but reasonable estimates have resulted when the expected static ice growth has been modified to account for dynamic processes.

Ice Cover Growth Resulting from Heat Transfer

Once an ice cover is formed, it may thicken through heat transfer processes as heat is lost to the atmosphere. In this case, the growth of ice thickness in inches (t_i) can be estimated from accumulated freezing degree days (AFDD). Freezing degree days (FDD) are first calculated for each day of the winter season:

$$\text{FDD} = (32 - T_a) \quad (1)$$

where T_a is the average daily air temperature in degrees Fahrenheit. A negative freezing degree day value represents a temperature warmer than freezing, while a positive freezing degree day represents temperatures below freezing. The FDD values for each day of the winter are summed to determine the net AFDD each day. The zero AFDD point is assigned to time in late fall or early winter when the AFDD curve goes from a negative to a consistently positive slope. Figure 4 presents an example of the relationship between average daily air temperature and net AFDD for Cairo, Illinois, for water year (WY) 1915.

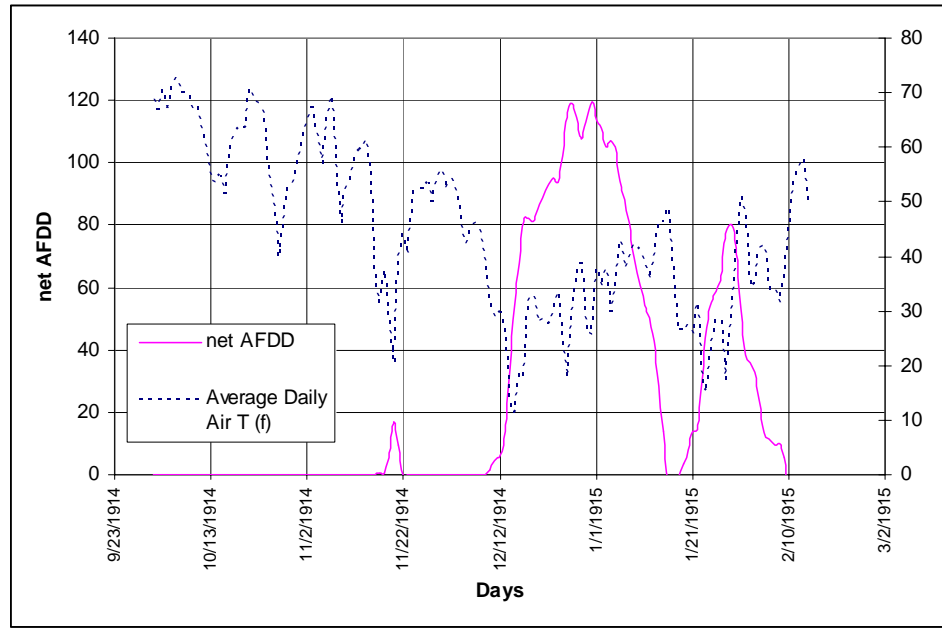


Figure 4. Example of average daily air temperature and net AFDD (Cairo, Illinois, WY 1915).

Ice thickness in inches is then estimated using the modified Stefan equation presented in USACE (2002):

$$t_i = C (AFDD)^{0.5} \quad (2)$$

where C is a coefficient, usually ranging between 0.3 and 0.6 and AFDD is in °F days (Table 1).

Table 1. Coefficient for use in modified Stefan equation with ice thickness in inches, AFDD in °F days (from USACE 2002).	
Condition	Typical value of C
Windy lake with no snow	0.8
Average lake with snow	0.5 to 0.7
Average river with snow	0.12 to 0.15
Sheltered small river	0.21 to 0.41

Using equation 2 with a coefficient of 0.6, we would predict that 300 AFDD would produce a 10-inch-thick sheet ice cover. Snow cover on top of the ice can insulate it, decreasing heat transfer and effectively lowering the coefficient used in equation 2. If ice cover growth is affected by underturning, shoving, or frazil deposition, the coefficient in equation 2 should be increased. Once the peak annual AFDD is reached and thawing days exceed freezing days, the coefficients shown in Table 1 are no longer applicable for equation 2. Ice thinning processes result from changes in the air and water thermal regimes and in the ice cover itself. Although some research (e.g., Bilello 1980) has indicated that a different set of coefficients could be used to describe thinning of the ice based on meteorological conditions, a complete examination of the problem has not been conducted to date. Thus, no coefficients are suggested for estimating ice thickness after the peak AFDD.

Process Used to Estimate Ice Thickness Based on Meteorological Data

In general, the process used to estimate ice thickness from thermally induced growth as discussed above is as follows:

1. Locate the National Weather Service (NWS) meteorological station closest to the site with the longest and most reliable period of record. Stations can be identified from lists available at the National Climatic Data Center (NCDC, <http://lwf.ncdc.noaa.gov/oa/ncdc.html>). Generally, first-order stations, which are usually fully instrumented and therefore record a complete range of meteorological variables, are preferred over cooperative

stations, which rely on manual measurements. Periods of record longer than 20 years are desired to reduce uncertainty in statistical analysis.

2. Obtain historical minimum and maximum daily air temperatures for the NWS station selected. This information can be obtained through NCDC or the local NWS Forecast Office.
3. Set up a spreadsheet calculating FDD and net AFDD for each winter, with time in Julian Days (JD) beginning with October 1 (i.e., October 1 = JD 1, October 2 = JD 2, etc.). When average daily air temperature is above 0°F (as is the case for many days in October, November, and December), the FDD will be negative. AFDD do not begin accumulating until the first sustained period of cold temperatures. Alternatively, FDD and net AFDD are calculated for some locations. For example, the U.S. Army Corps of Engineers St. Paul District River Ice Network provides seasonal AFDD information for selected stations in the upper Midwest (<http://www.mvp-wc.usace.army.mil/ice/afdd/>). ERDC-CRREL often has calculated this information in connection with projects for Corps Districts or other customers.
4. Identify the maximum net AFDD for each winter and the date of the maximum AFDD in JD.
5. Estimate maximum ice thickness for each year based on the maximum net AFDD using the modified Stefan equation. The coefficient used in the Stefan equation may be verified or modified after comparing estimated-to-measured ice thickness, if measurements are available. The ERDC-CRREL Ice Jam Database (<http://www.crrel.usace.army.mil/ierd/ijdb/>) contains some information on ice thickness; other information may be available from the local office of the U.S. Geological Survey, hydropower facilities, or other state or local agencies.
6. Perform a statistical analysis to select the design ice thickness. Generally, the mean thickness and the thickness at the $\pm 95\%$ confidence limits are required for design purposes.

Example

As an example, suppose estimates of a thermally grown ice cover are desired for the Peabody River in Gorham, New Hampshire. Data from the NWS weather station in nearby Berlin, New Hampshire, for the period 1948 to 1969, 1971 to 2000 are available. Annual peak net AFDD and the date of the peak net AFDD are shown in Figures 5 and 6. The mean maximum AFDD is 1463 °F days and the mean date of the maximum AFDD is 24 March for this period. The smallest recorded annual maximum AFDD was 991 °F days (17 March 1999), and the largest was 2018 °F days (16 March 1968). The date of the maximum AFDD is rather late for New England and ranges between 1 March (1958) and 13 April (1972), with a mean date of 24 March for this period.

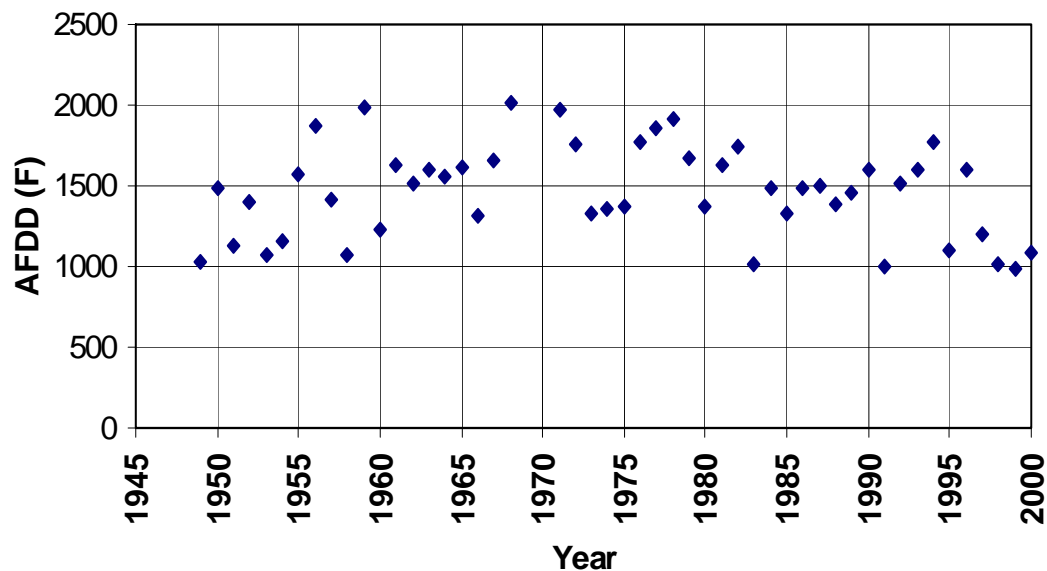


Figure 5. Net AFDD data calculated for Berlin, New Hampshire, NWS station.

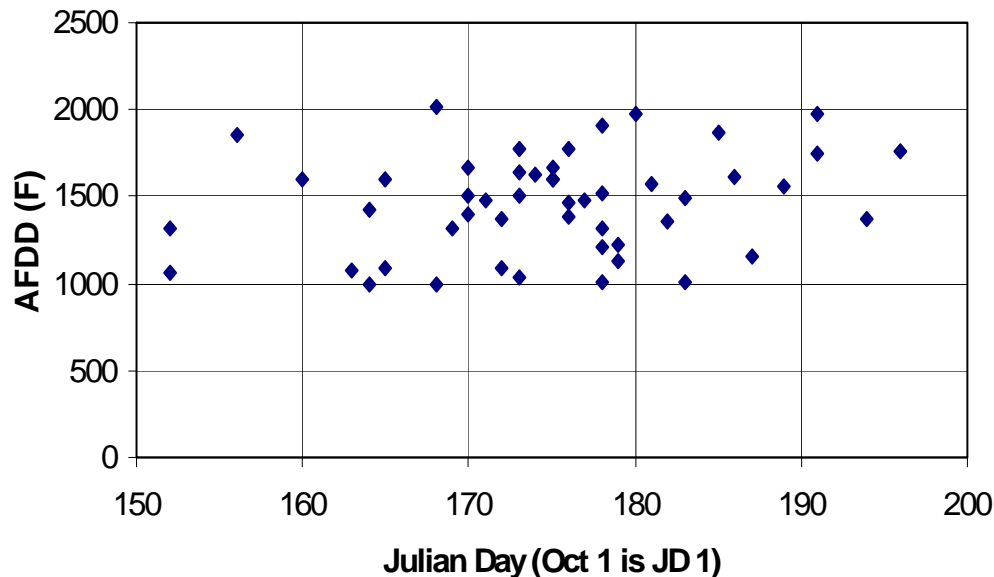


Figure 6. Date of maximum net AFDD, Berlin, New Hampshire.

Assuming a coefficient of 0.41 for this relatively sheltered small river, the maximum thermally grown ice thickness of the Peabody River would be expected to range between 13 inches and 18.4 inches, with an average of 15.7 inches. However, this steep, turbulent river produces large amounts of frazil ice in early winter, which tends to deposit beneath the ice cover, thickening the ice compared to a thermally grown ice cover. On the other hand, large amounts of snow fall in the region, insulating the ice cover, and thus decreasing the thickness compared to a thermally grown ice cover.

The reasonableness of the coefficient was checked by measuring the ice thickness at five locations on the Peabody River in mid-January 2001. Measurements ranged from 10.5 inches at the upstream end of the study reach to 22.5 inches at the downstream end of the study reach, averaging 18.4 inches. Observed snow cover on top of the ice ranged from 36 inches where the ice was thinnest to 24 inches near the lower end of the study reach, averaging 32 inches. AFDD at the time was 688 °F days, corresponding to an estimated thickness of 10.7 inches as a result of thermal ice growth using the coefficient of 0.41. Based on the observed ice thickness, and considering both the snow cover and frazil deposition at this location, a coefficient of about 0.7 fits the observed ice thickness and would be considered reasonable for this site.

Conclusion

Estimates of ice cover thickness are often necessary for hydraulic analyses of ice-affected rivers or for design of bridges or other riverine structures. Although ice cover formation and growth can be a highly complex and variable process, estimates of ice cover thickness can be made using meteorological data. The modified Stefan equation is suitable for use in estimating ice thickness in many cases. Whenever possible, the estimated ice thickness at a particular site should be compared to actual ice thickness observations to evaluate the reasonableness of the coefficients given the physical processes governing ice cover growth.

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